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Effect of Dielectric Substrate on Infinite Arrays of Single-Polarized Vivaldi Antennas

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ABSTRACT

The effect of dielectric substrate on the performance of infinite arrays of single-polarized Vivaldi antennas is studied by computing the input impedance of an antenna in an array environment using full wave method of moments techniques. It is found that dielectric permittivity plays an important role in the wideband performance of such arrays, and comparison with dielectric-free cases for similar geometries is also included to bring out the impact of the presence of the substrate. The effect of substrate thickness is also studied. Results are shown to explain the trends and characteristics of parametric variation, which are useful in creating a new design, or in optimizing an existing one involving Vivaldi arrays aimed at wideband performance.

1. Introduction

The Tapered Slot Antenna (TSA) was first introduced by Lewis et al [1] in 1974, followed by Gibson [2] in 1979, who named it 'Vivaldi'. An important characteristic of the Vivaldi or notch antenna as it is also called, is its wide-scan, wide-band performance, when used as an element in a scanning array. These arrays are relatively easy to fabricate using printed circuit techniques, and the feed techniques are also convenient: microstrip or stripline is used, depending on the application and scale. Recognizing the potential of the TSA as an array element, extensive work has been done over the past couple of decades, resulting in a good amount of background on the subject [3]-[8].

An insight into the cause-effect relationship of different design parameters and antenna array performance is necessary to develop a successful design. Preliminary studies [9] have laid the foundation for study of parametric dependencies in infinite TSA arrays. One important parameter that has been hitherto unexplored is the dielectric substrate. Though many of the designs that have been successfully implemented employ stripline feed circuits [10,11], the effects of varying the dielectric parameters (permittivity and thickness) have not been published. Antennas without substrate, i.e., dielectric-free antennas, have the advantage that they are less bulky, less expensive, and still yield reasonably good results [12]. This necessitated a comparative study of dielectric-free antennas and antennas with similar geometries employing stripline feeds, which was done in [13] using one value of dielectric permittivity. The present paper attempts to evaluate the effect of dielectric substrate by studying the performance for different permittivities, and also the dielectric-free case, over 27 different geometries. Further, the effect of thickness of dielectric is examined. The study was conducted by using the infinite-array analyses [14,15] that have been developed at the University of Massachusetts and verified by comparison to waveguide simulator experiments and to other computational methods.

2. Design Parameters and Method of Analysis

The design parameters of a Vivaldi antenna, called its 'geometry', are defined in Figures 1 - 3. All parameters except the ones under study are fixed based on previous studies [13]. The H-plane spacing is equal to the E-plane spacing, which is 8 cm (equal to half-wavelength at 1.875 GHz). For the permittivity study, each geometry is identified by the combination of three variable metal fin parameters, the opening rate **Ra**, antenna depth **D**, and cavity size **Dsl**. The variation of permittivity is studied for each such geometry (27 in all), with a constant thickness of t=0.32 cm (126 mils). Similarly, the variation of thickness is studied for several geometries, and three values of relative permittivity ε_r. Tables I and II list values of the variable parameters involved.

The several cases that were selected for permittivity study, dielectric-free and stripline-fed with ε_r = 2.2, 4 and 6 (Figure 4(a)), yield sufficiently different results to indicate the impact of ε_r on array performance and they span the range of substrates that are often considered for TSA array fabrication. The dielectric-free cases (Figure 4(b)) are of considerable interest because the cost and weight of microwave substrates used in stripline-fed arrays are too high for many applications. Antennas employing substrate thickness ranging from 30 mils to 150 mils are also studied, for three different dielectric substrates ε_r =2.2, 3.5 and 6.

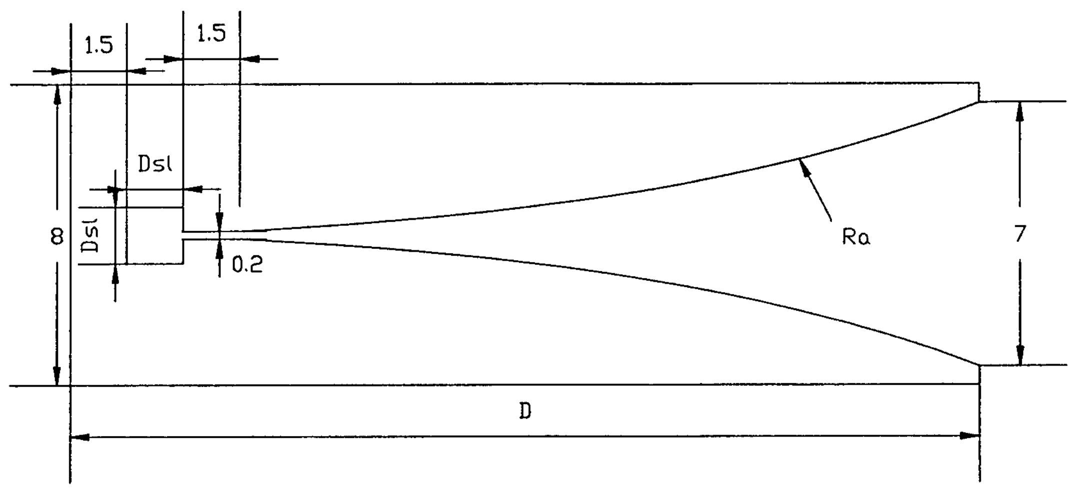

Figure 1. Metal Fin Parameters (All dimensions in cm)
Ra: 0.1, 0.2, 0.3
D: 24, 32, 40
Dsl: 1.5, 2.0, 2.5

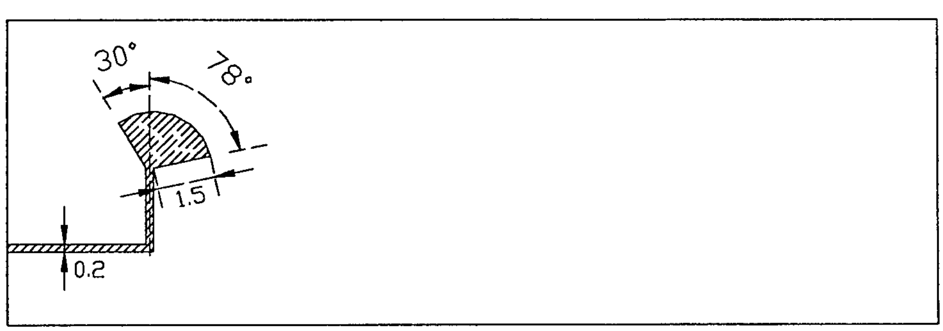

Figure 2. Feed – Stub Parameters

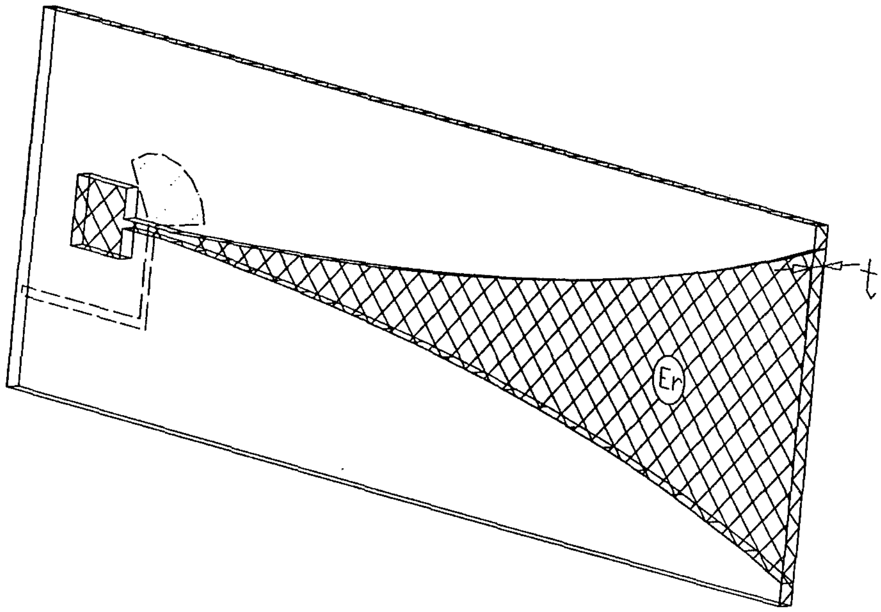

Figure 3. Dielectric Parameters

TABLE I
PARAMETERS FOR PERMITTIVITY STUDY

Relative Permittivity, ε_r	Substrate Thickness, t
2.2	0.32 cm (126 mils)
4.0	0.32 cm (126 mils)
6.0	0.32 cm (126 mils)
9.8*	0.32 cm (126 mils)

* $\varepsilon_r = 9.8$ case is computed only for one geometry (Dsl=1.5, D=24, Ra=0.1).

TABLE II
PARAMETERS FOR THICKNESS STUDY

Substrate Thickness, t	Relative Permittivity, ε_r
0.0762 cm (30 mils)	2.2, 3.5, 6
0.1575 cm (62 mils)	2.2, 3.5, 6
0.254 cm (100 mils)	2.2, 3.5, 6
0.381 cm (150 mils)	2.2, 3.5, 6

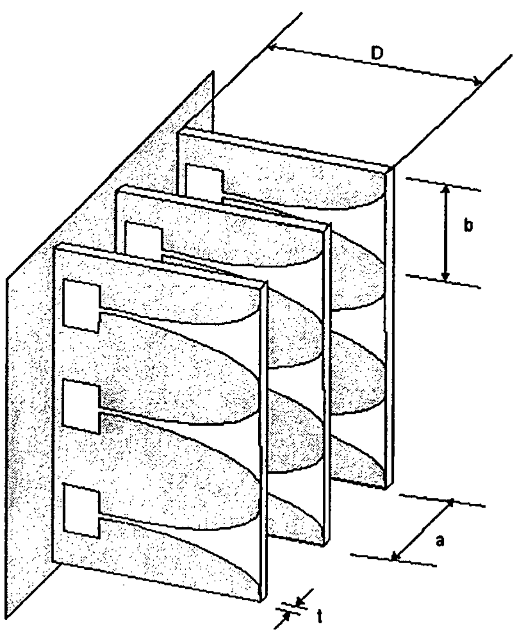

Figure 4. (a) Single-polarized TSA array with dielectric.

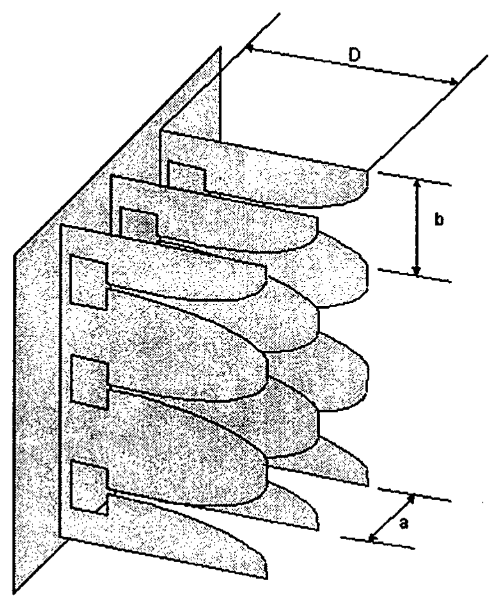

Figure 4. (b) Single-polarized TSA array without dielectric.

Dielectric-free antennas are comprised of a metal fin and are fed by a balanced circuit or by microstripline on a small piece of substrate covering only a small portion of the antenna near the narrowest part of the slotline.

Two different Frequency – Domain Method of Moments (FD-MoM) computational schemes were employed to compute the input impedance of the dielectric and dielectric-free antennas. Both methods employ the unit cell approach and Floquet modes are used to represent infinite periodicity. The former [14] involves magnetic currents in the slot region while the latter [15] involves calculation of electric surface currents on the metal fin. The magnetic current approach is beneficial to model antennas with a dielectric sandwiched between the two metal fins.

Care was taken to maintain the same electrical point of reference for input impedances calculated by the different computation schemes, which is at the narrowest part of the slotline (the stripline-slotline transition in the case of dielectric). The dielectric-free (AIR) computation scheme directly yields the input impedance at the desired point; the dielectric (stripline-fed) computation yields the input impedance at the start of the stripline, as shown in figure 5 (b). A transmission line model (Figure 6) is used to transform the input impedance from the start of the stripline to the desired reference plane at the stripline – slotline transition.

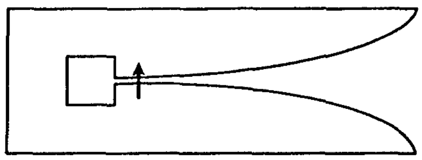

Figure 5(a). Feed mode on AIR

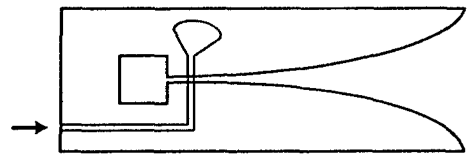

Figure 5(b). Feed mode on stripline-fed

The presence of the capacitive radial stub enhances wideband matching; however, its capacitance is excluded when comparing the input impedance with that of the dielectric case, in which there is no capacitive stub. The reactance of the radial stub is calculated using the MoM code for dielectric antennas but using basis functions *only on the feedline and stub.* This corresponds to analyzing a non-radiating stripline circuit. Previous work has shown that the stub reactance obtained from such an analysis yields good results. After the reactance is computed, it is subtracted from the input impedance at the stripline-slotline transition, which is obtained by employing the equivalent circuit shown in figure 6.

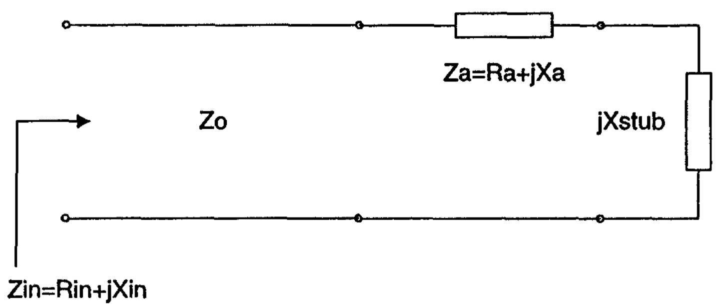

Figure 6. Equivalent circuit for stripline-fed

The following comments are to be noted with respect to the results that follow:

- For the dielectric-free case, the VSWR is calculated with respect to a normalizing impedance of 80Ω, which yields the best wide-band VSWR for most of the geometries.
- For the dielectric case, the VSWR is calculated by normalizing to the impedance value that yields for that case the best VSWR

through the whole band. This normalizing impedance is usually 40-80Ω.

- In the dielectric case, the impedance used to calculate the VSWR includes the radial stub reactance, since the capacitance of the stub is an integral part of the actual antenna and it usually improves the wideband VSWR.

3. Results and Discussion

3.1. Dielectric Permittivity (ε_r):

As stated earlier, the effect of dielectric substrate was studied over twenty-seven different geometries (of the metal fin) and compared against the dielectric-free case of the corresponding same structure. Figures 7, 8 and 9 below depict the impact of dielectric on the input impedance for a particular geometry. All impedances are evaluated for a broadside beam of the infinite array.

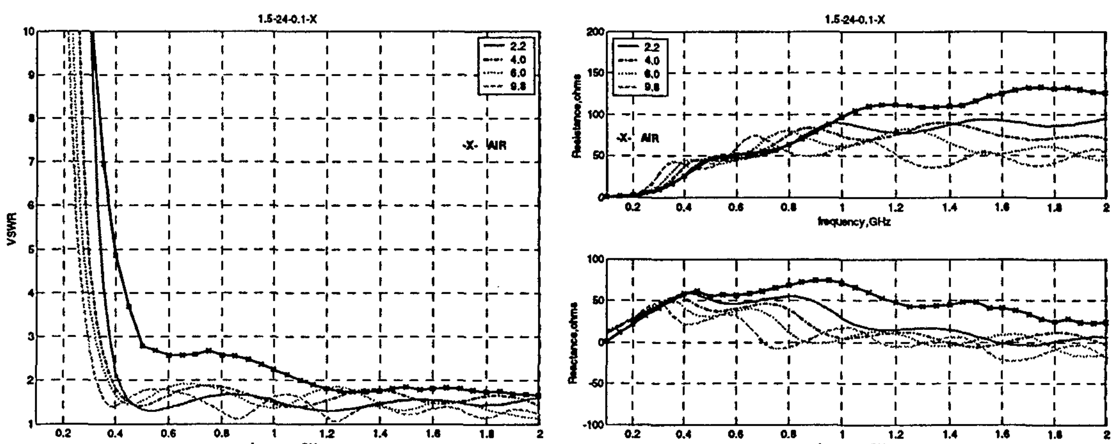

Figure 7. Effect of dielectric permittivity (ε_r =2.2, 4.0, 6.0, 9.8, slotline cavity size=1.5 cm, antenna length=24 cm, rate of exponential taper=0.1 cm^{-1})

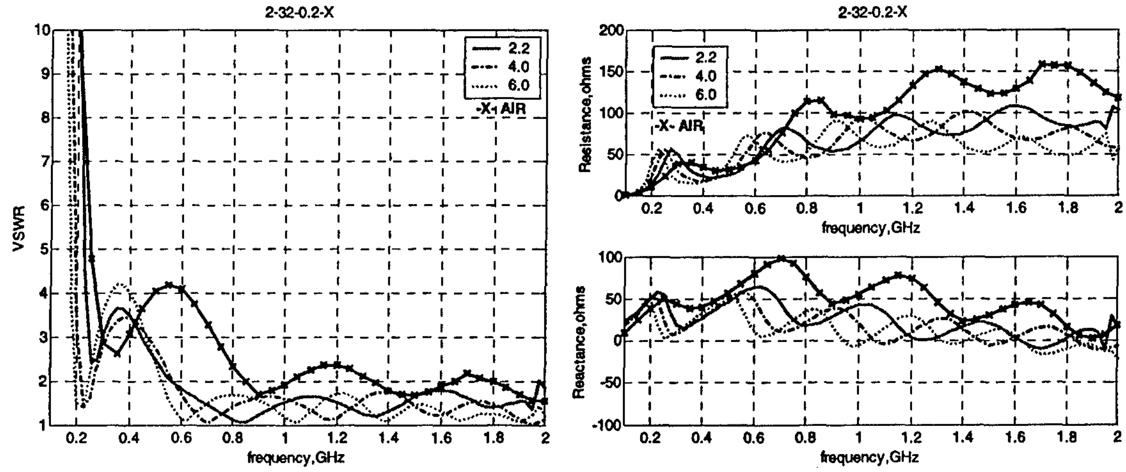

Figure 8. Effect of dielectric permittivity (ε_r =2.2, 4.0, 6.0 slotline cavity size=2 cm, antenna length=32 cm, rate of exponential taper=0.2 cm^{-1})

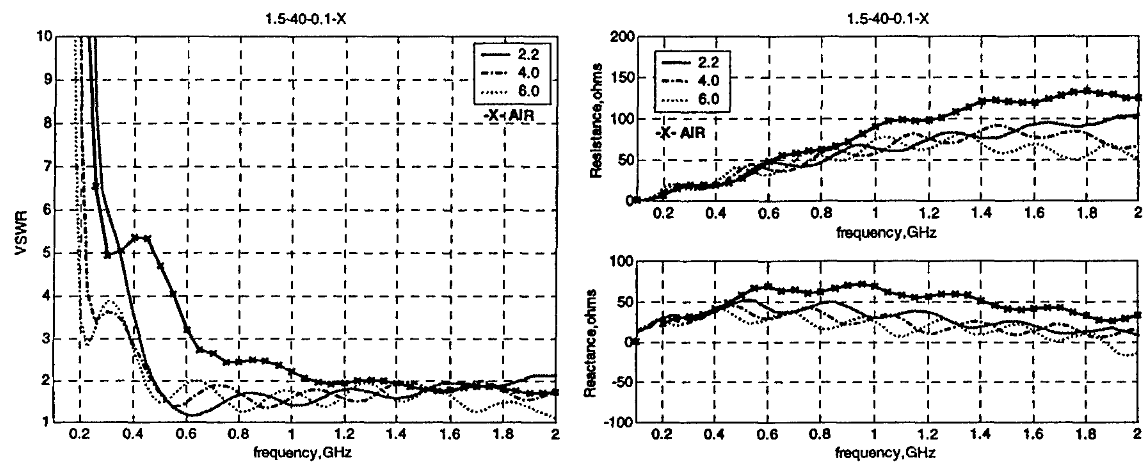

Figure 9. Effect of dielectric permittivity (ε_r =2.2, 4.0, 6.0 slotline cavity size=1.5 cm, antenna length=40 cm, rate of exponential taper=0.1 cm^{-1})

The following inferences can be made from the above and other similar comparisons for different geometries:

- The dielectric substrate has a significant impact on the slope and curvature of the average resistance. For the dielectric-free case, the average resistance increases almost monotonically across the operating frequency range. Hence it is difficult to pick a normalizing resistance that would yield reasonable VSWR for a wide band performance. With the presence of dielectric, however, the average resistance appears to increase and stay almost constant through a considerable range of frequencies; as the permittivity increases, the average resistance towards higher frequencies starts to decrease. In fact, for the ε_r =9.8 case (Figure 7), a second degree of oscillation can be discerned by the fact that the average resistance reaches a maximum below midband, then goes to a minimum, and starts to increase again towards the high frequency end. As is evident from the VSWR plot, the antenna with ε_r =9.8 has the widest operating frequency range.
- The antenna with the highest permittivity has its first resistive peak at the lowest frequency. This results in a lower minimum usable frequency, increasing bandwidth. In comparison, the slope of the resistance of the dielectric-free antenna results in a resistive peak at a much higher frequency, inhibiting its bandwidth.
- The number of oscillations (resonances) in resistance and reactance increases with permittivity. This is similar to the effect seen as the depth of the element increases. It appears that the number of oscillations is approximately determined by the depth of the antenna scaled by the dielectric loading of ε_r.

The strong dependence of low-frequency resistance on ε_r might be used in some cases, to overcome one of the drawbacks of Vivaldi arrays - antenna depth. The low-frequency operation of a Vivaldi array is dependent on the antenna depth - for a fixed dielectric permittivity, longer antennas tend to have greater bandwidth [13]. If there is a depth constraint, a short antenna with high permittivity might replace a longer antenna with low permittivity, provided the decrease in depth does not cut off more bandwidth than that which can be compensated by the increase in permittivity. Hence it is a balance that is to be achieved between the two parameters depth and permittivity, to optimize performance.

As shown in Figure 10, the 24-cm antenna with ε_r = 6 operates over a wider bandwidth with VSWR<2 than a well-designed antenna with ε_r = 2.2 that is

40 cm deep. For this particular geometry, the 32-cm antenna operates even better, since it balances the effects of depth and permittivity.

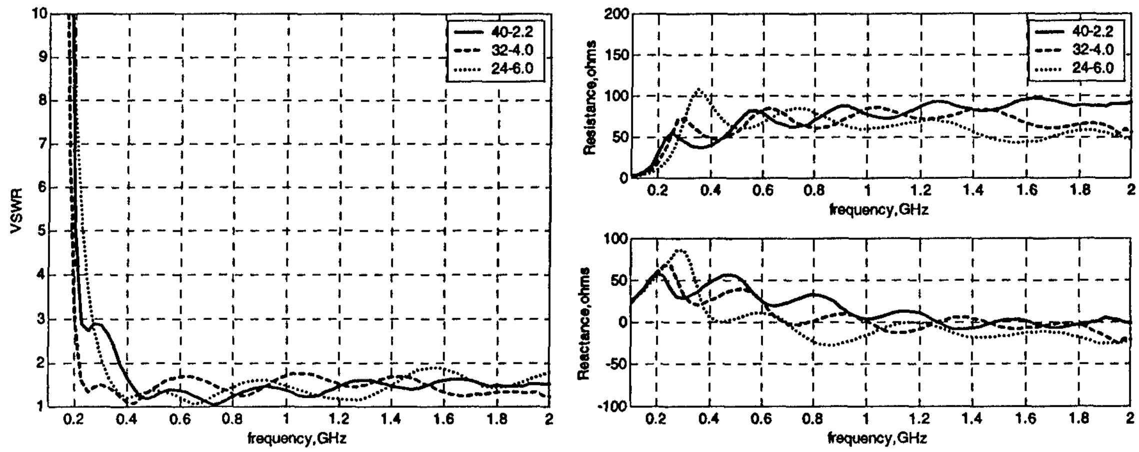

Figure 10. Depth compensation by higher ε_r (slotline cavity size =2.5 cm, opening rate =0.1)

3.2. Substrate thickness (t):

The effect of substrate thickness was examined for a thickness range of 30 mils to 150 mils, over three dielectrics, ε_r =2.2, 3.5 and 6. Other parameters of the geometry are kept constant. Figures 11, 12 and 13 depict the variation of input impedance for one particular geometry.

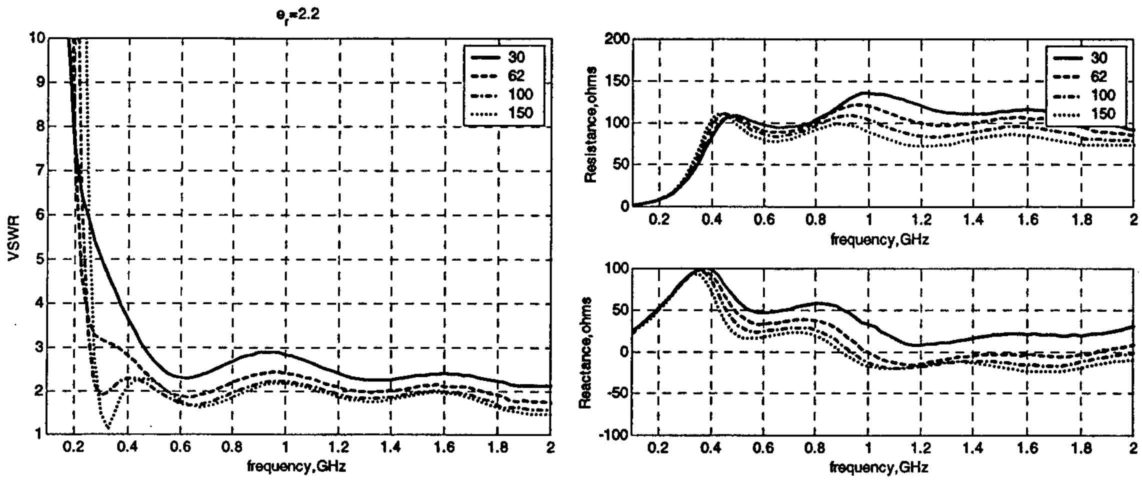

Figure 11. Effect of substrate thickness (t =30, 62, 100, 150 mils, $\varepsilon_r = 2.2$, slotline cavity size=2.5 cm, antenna length=24 cm, rate of exponential taper=0.1 cm^{-1})

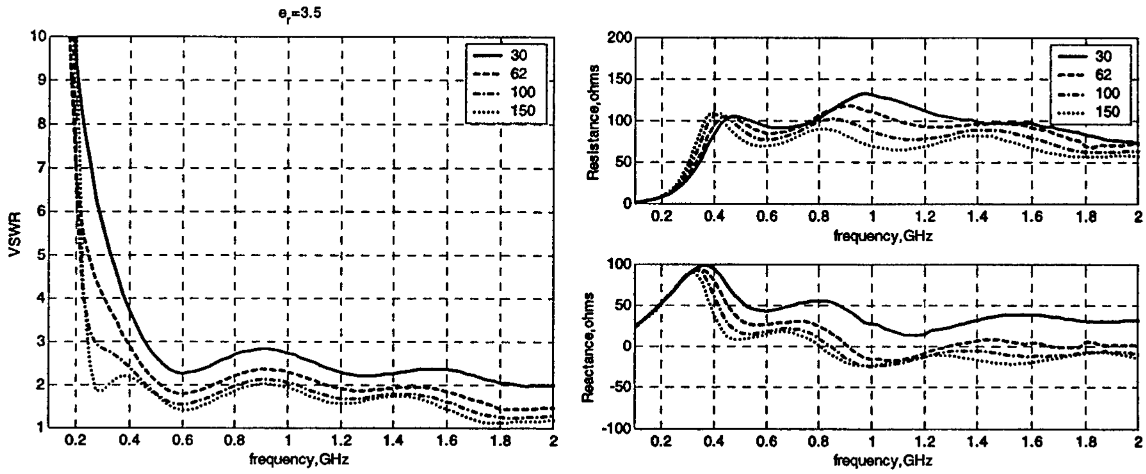

Figure 12. Effect of substrate thickness (t =30, 62, 100, 150 mils, $\varepsilon_r = 3.5$, slotline cavity size=2.5 cm, antenna length=24 cm, rate of exponential taper=0.1 cm^{-1})

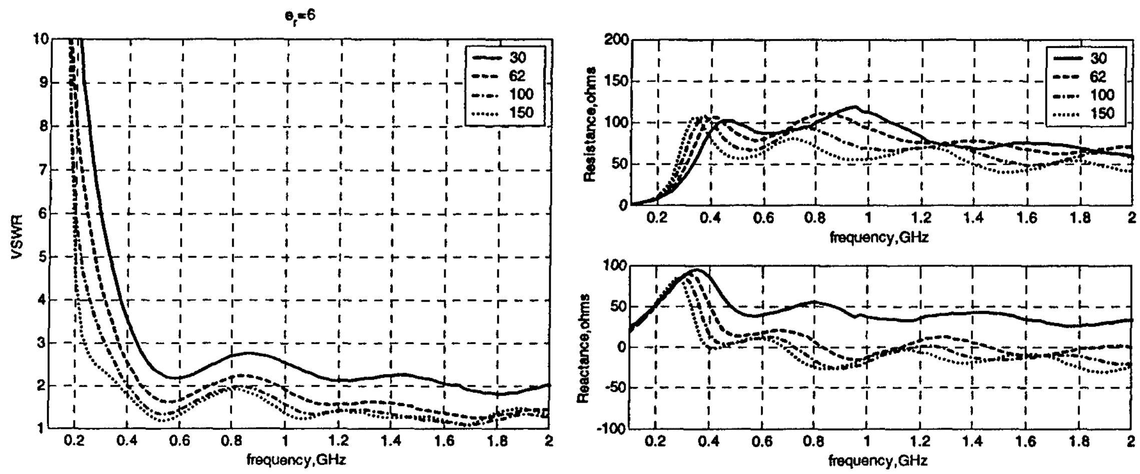

Figure 13. Effect of substrate thickness (t =30, 62, 100, 150 mils, ε_r = 6.0, slotline cavity size=2.5 cm, antenna length=24 cm, rate of exponential taper=0.1 cm^{-1})

The effect of changing substrate thickness can be summarized in the following trends:

- Substrate thickness affects the lower frequency performance of the antenna. With increasing thickness, the minimum usable frequency decreases, thus resulting in a larger band of operation. This effect can be seen especially in Figures 12 and 13, where the high dielectric constant accentuates the trend.
- Thicker substrates result in lower high frequency resistance.
- Thicker substrates result in lower reactance. The low-frequency inductive peak decreases as substrate thickness increases and the high-frequency reactance is near zero.

4. Conclusion

The effect of dielectric substrate is studied and it is found that

- Dielectric loading improves the low-frequency performance considerably in comparison to the dielectric-free case.

- Substrates of higher permittivities result in better bandwidths of operation for a given benchmark VSWR.
- The effects of dielectric permittivity can be utilized to counter disadvantages due to variation in other parameters such as changes in the metal fin geometry. For instance, a shorter antenna might be employed to operate over the same frequency range if a higher permittivity substrate is used (shorter antennas tend to have higher minimum usable frequencies).
- Substrate thickness also contributes to bandwidth enhancement-thicker substrates lead to lower frequencies of operation and lower antenna inductance.

5. Acknowledgements

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